Probing The Weak Boson Sector in ZZ Production at the LHC

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in preparation

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1 – Motivation

- The SM uniquely predicts the form of the self-couplings of the W, Z and photon.
- The most general phenomenological effective Lagrangian allows WWV ($V = \gamma$, Z), $Z\gamma V$ and ZZV couplings
- The introduction of general trilinear gauge boson couplings is similar to the introduction of arbitrary vector and axial vector couplings g_V and g_A of gauge bosons to fermions
- The WWV couplings can be probed in W^+W^-, $W^\pm\gamma$ and $W^\pm Z$ production
- The $Z\gamma V$ couplings can be probed in $Z\gamma$ production
- The ZZV couplings can be probed in ZZ production

- ZZ production has recently been observed at LEP2 and (weak) limits on the ZZV couplings have been obtained

- So far, at the Tevatron, ZZ production has not been observed

  ☞ only the WWV and $Z\gamma V$ couplings have been tested at hadron colliders

- This will change in Run II and at the LHC

- Highlights of our calculation:

  ☞ we calculate $p\overset{(-)}{p} \to ZZ$ for general ZZV couplings

  ☞ the calculation is performed at tree level in the double pole approximation

  ☞ Z decays together with decay correlations are fully included

2 – ZZV Couplings

- The most general ZZV vertex can be parameterized by two free parameters, f_4^V and f_5^V which are both zero in the SM at tree level:

$$\Gamma_{ZZV}^{\alpha\beta\mu}(q_1, q_2, P) =$$

$$\frac{P^2 - M_V^2}{M_Z^2}\left[i f_4^V \left(P^\alpha g^{\mu\beta} + P^\beta g^{\mu\alpha}\right)\right.$$

$$\left. + i f_5^V \varepsilon^{\mu\alpha\beta\rho}(q_1 - q_2)_\rho \right]$$

  ☞ both couplings violate C invariance
  ☞ f_4^V violates CP invariance
  ☞ f_5^V violates P invariance

- The overall factor $P^2 - M_V^2$ is implied by Bose symmetry for on-shell V and/or by gauge invariance for $V = \gamma$

- These additional factors indicate that anomalous ZZV couplings can only arise from $dim \geq 6$ operators and hence their effects should be suppressed in any scenario of new physics beyond the SM.
- SM, 1-loop:

$$\begin{aligned} f_4^V &= 0 \\ f_5^V &= \mathcal{O}(10^{-4}) \end{aligned}$$

(Gounaris et al.)

- In order to preserve S-matrix unitarity, the anomalous couplings have to be form factors which $\to 0$ at large energies.

$$f_i^V(q^2) = \frac{f_{i0}^V}{(1 + q^2/\Lambda_{FF}^2)^n}$$

q^2 is the squared momentum transfer. Λ_{FF} is $\sim$ the scale of new physics.

- The values of the form factors at small momentum transfer, as well as n are constrained by partial wave unitarity of the

$$f\bar{f} \to ZZ$$

amplitude at arbitrary center of mass energies:

$$\left| f_{40,50}^{V} \right| \leq \frac{\beta^V}{\Lambda_{FF}^3} \; \frac{\left(\frac{2}{3}\,n\right)^n}{\left(\frac{2}{3}\,n - 1\right)^{n-3/2}}$$

with

$$\beta^\gamma = 0.107 \text{ TeV}^3 \qquad \beta^Z = 0.089 \text{ TeV}^3$$

→ $n > 1.5$

→ choose $n = 3$ in the following to leave room for resonances etc.

3 – Phenomenology

- final states of interest at the LHC:

$$\begin{aligned} ZZ &\to \ell_1^+\ell_1^-\ell_2^+\ell_2^- \\ ZZ &\to \ell^+\ell^- + \not{p}_T \\ ZZ &\to \ell^+\ell^- + 2\ \mathrm{jets} \\ ZZ &\to \not{p}_T + 2\ \mathrm{jets} \end{aligned}$$

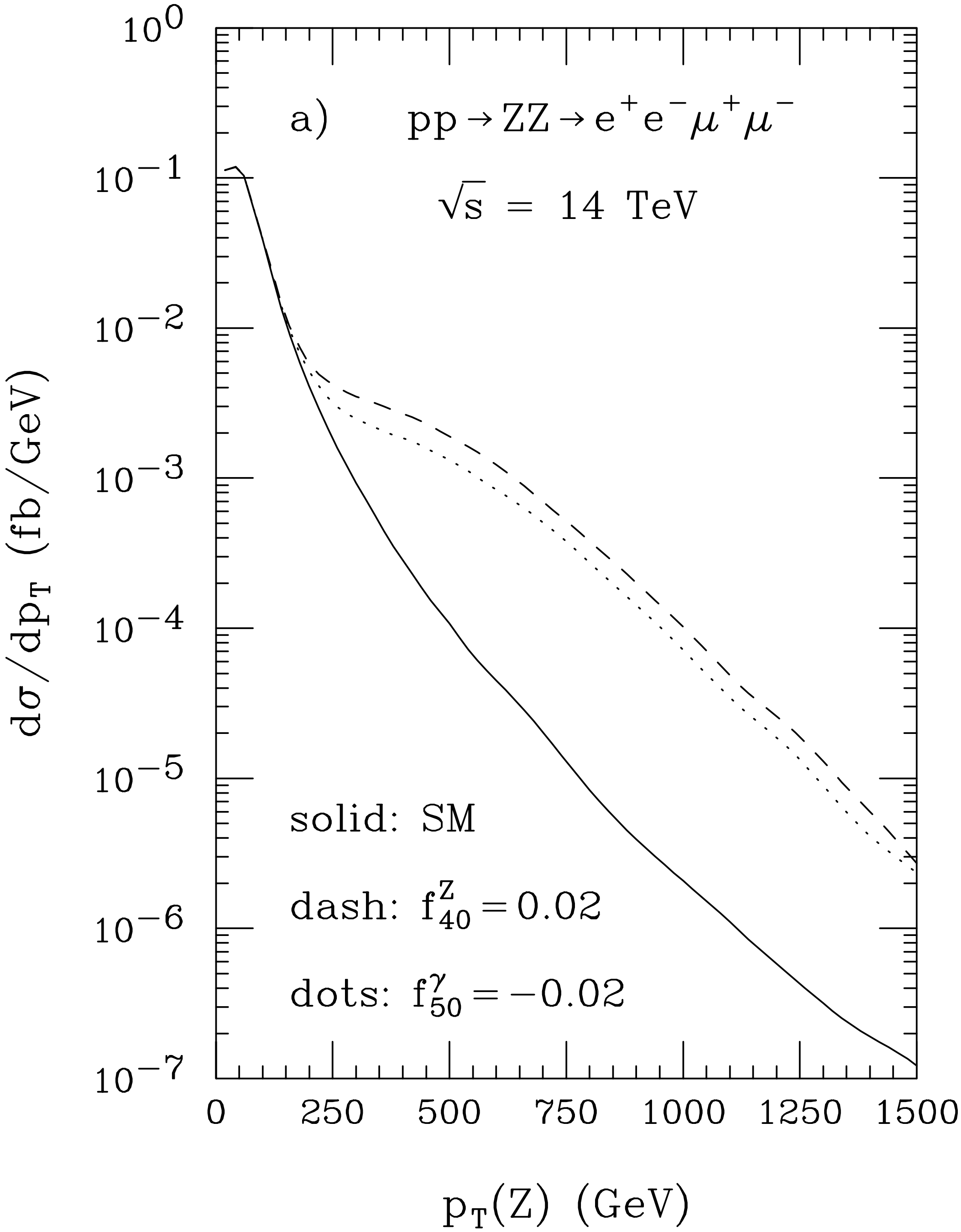
- choose $\Lambda_{FF} = 2$ TeV at the LHC in the following
- $ZZ \to \ell_1^+\ell_1^-\ell_2^+\ell_2^-$

  ☞ is essentially background free

  ☞ cuts: $p_T(\ell) > 15$ GeV, $|\eta(\ell)| < 2.5$, 76 GeV$< m(\ell\ell) < 106$ GeV

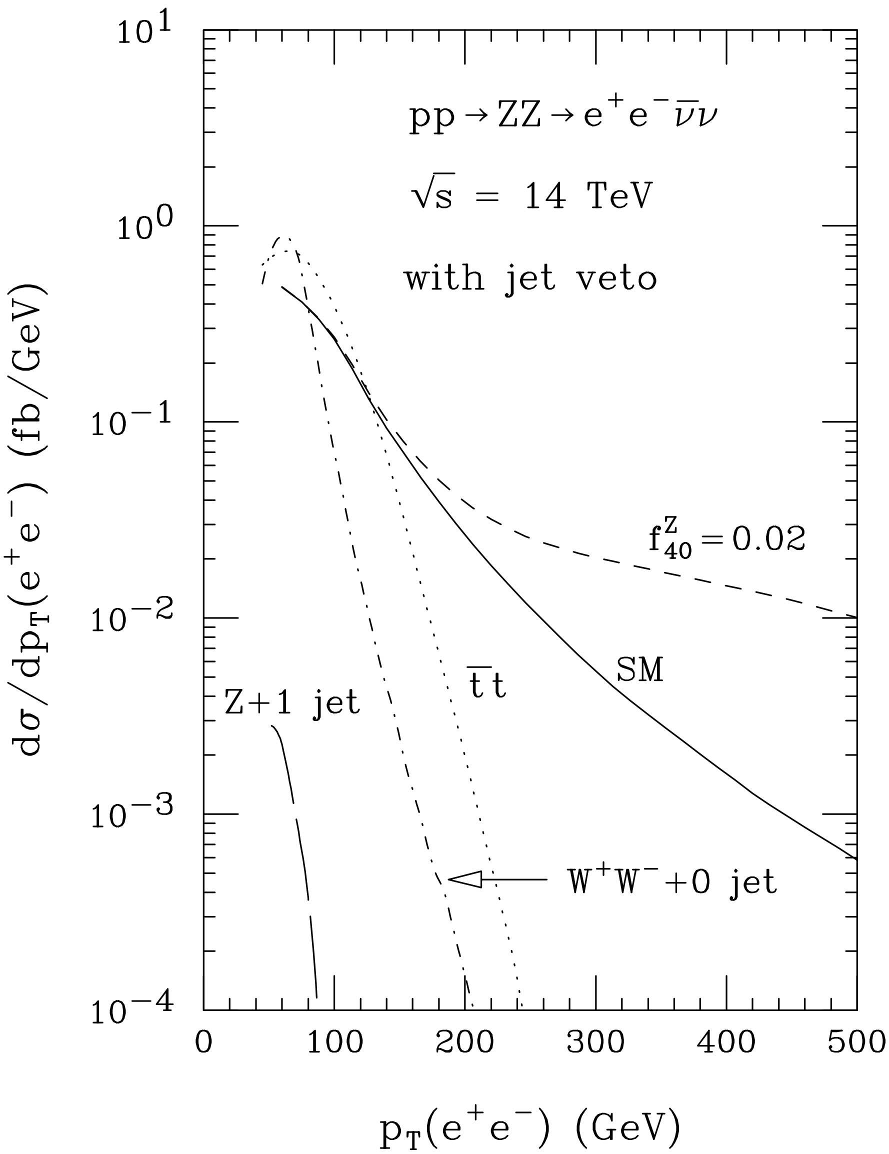
  ☞ signature for anomalous ZZV couplings: broad increase in m_{ZZ}, $p_T(Z)$ and $p_T(\ell)$ distributions at large values

☞ LHC:



a) pp→ZZ→e⁺e⁻μ⁺μ⁻
√s = 14 TeV
solid: SM
dash: $f_{40}^{Z}=0.02$
dots: $f_{50}^{\gamma}=-0.02$
$d\sigma/dp_T$ (fb/GeV)
$p_T(Z)$ (GeV)
10^{0}
10^{-1}
10^{-2}
10^{-3}
10^{-4}
10^{-5}
10^{-6}
10^{-7}
0
250
500
750
1000
1250
1500

- $ZZ \to \ell^+\ell^- + \not{p}_T$
  - ☞ main backgrounds: $t\bar{t}$ and W^+W^- production
  - ☞ impose $\not{p}_T > 50$ GeV) cut
  - ☞ veto jets with $p_T(j) > 50$ GeV, $|\eta(j)| < 5$



☞ background does not affect sensitivity to ZZV couplings

- $ZZ \to \ell^+\ell^- + 2$ jets and $ZZ \to p\!\!\!/_T + 2$ jets

☞ cuts:

$$76 \text{ GeV} < m(jj) < 106 \text{ GeV}$$

$$p_T(j) > 30 \text{ GeV} \qquad |\eta(j)| < 3$$
$$\Delta R(\ell j) > 0.6 \quad \Delta R(jj) > 0.6$$

$$p\!\!\!/_T < 40 \text{ GeV} \quad \text{for} \quad ZZ \to \ell^+\ell^- + 2 \text{ jets}$$

for $ZZ \to p\!\!\!/_T + 2$ jets:

$$p\!\!\!/_T > 60 \text{ GeV}$$
$$p_T(\ell) < 10 \text{ GeV} \quad \text{for} \quad |\eta(\ell)| < 2.5$$

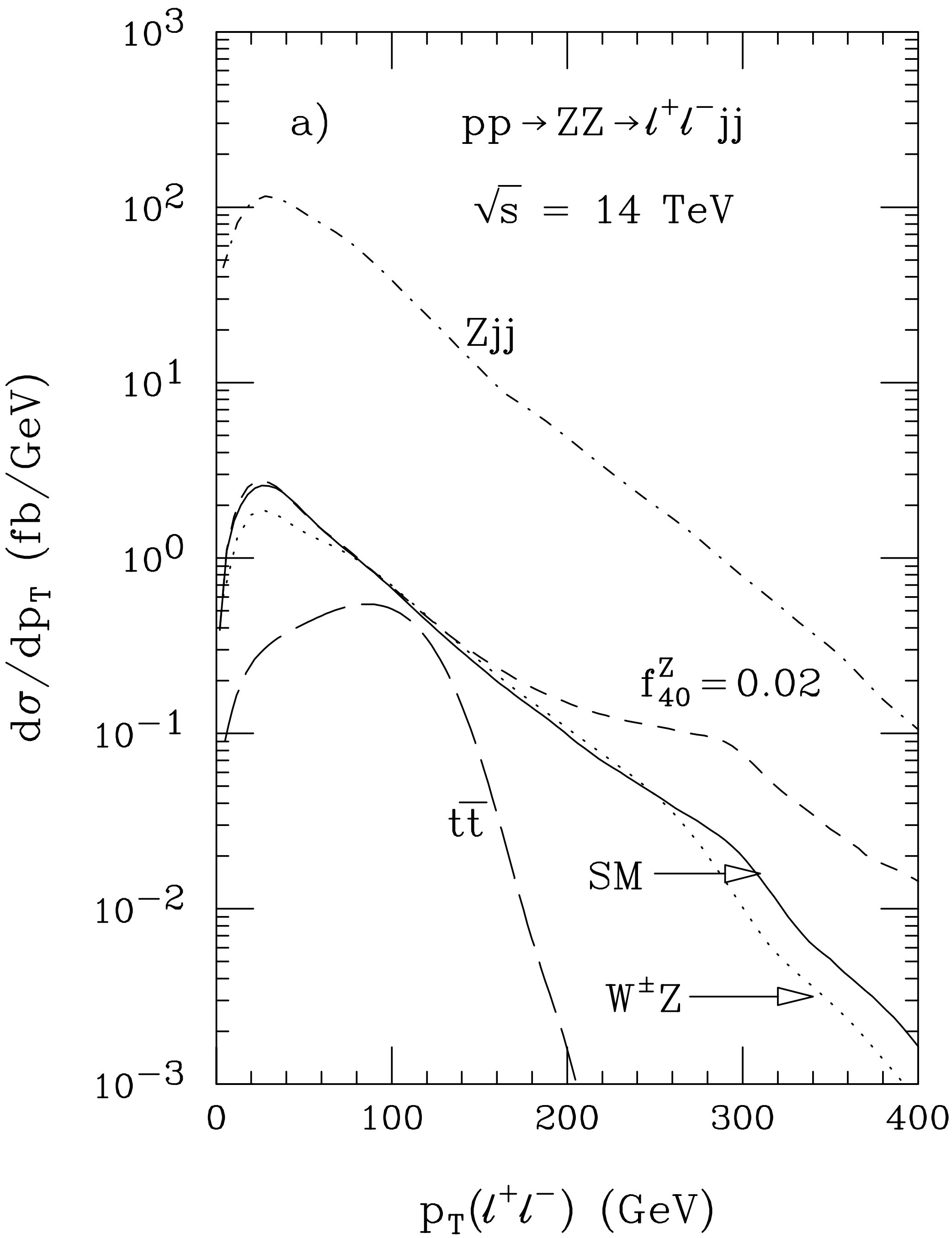
☞ advantage: large branching fractions:
$B(ZZ \to \ell^+\ell^- + 2 \text{ jets}) \approx 9.4\%$,
$B(ZZ \to p\!\!\!/_T + 2 \text{ jets}) \approx 28\%$

☞ main backgrounds: $Z + 2$ jets, $t\bar{t}$ and WZ production

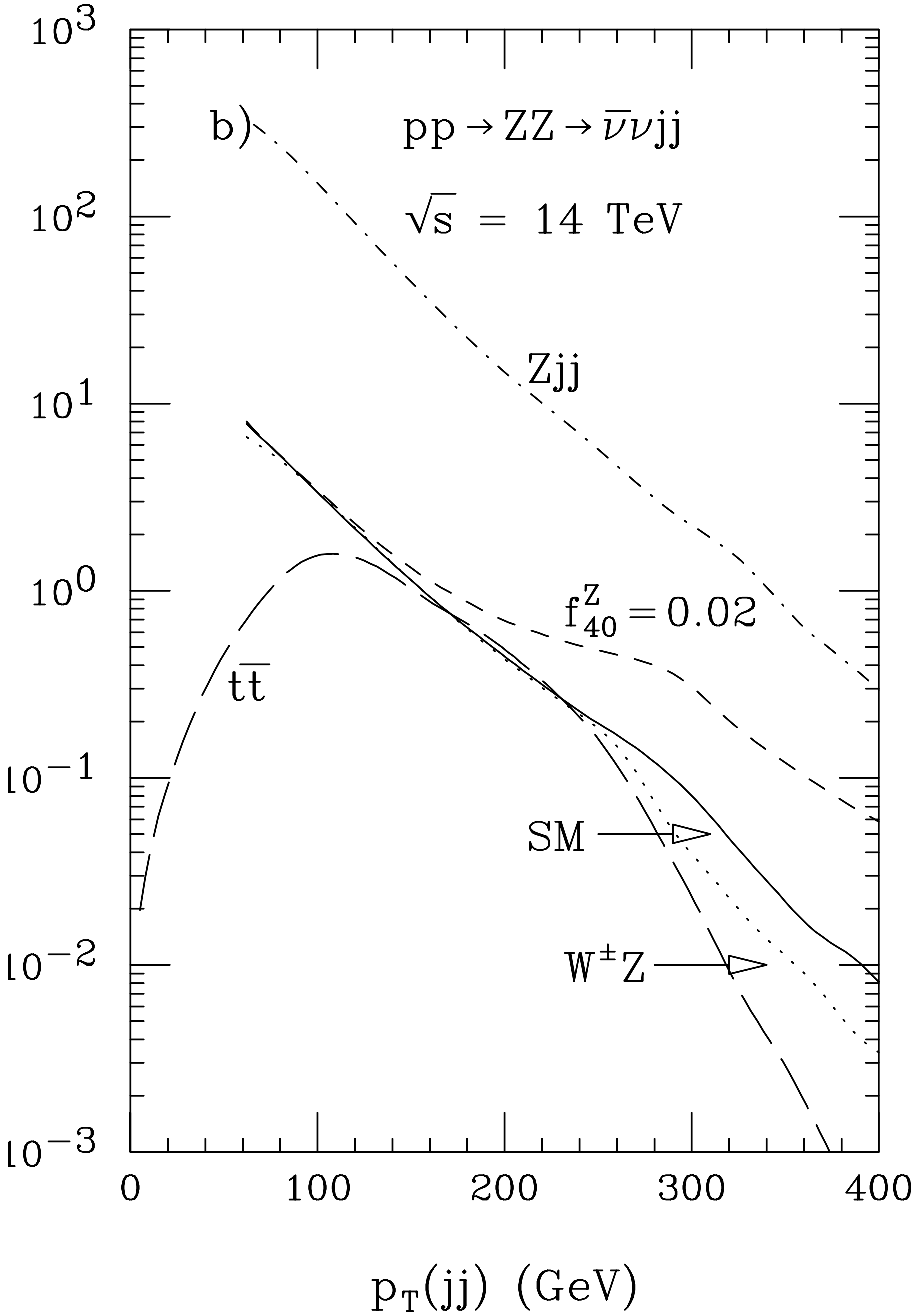
☞ $t\bar{t}$ background small at high p_T after $p\!\!\!/_T < 40$ GeV or lepton veto cut

☞ $Z+2$ jets background is about a factor 50 larger than SM ZZ production at the LHC

☞ LHC: $\ell^+\ell^- jj$



☞ LHC: $\not{p}_T jj$ (difficult to trigger on?)



- sensitivity limits

  ☞ perform χ^2 test for $p_T(\ell^+\ell^-)$ distribution

  ☞ use $p_T(jj)$ distribution for $ZZ \to \not{p}_T jj$

  ☞ allow for a 30% normalization uncertainty of SM cross section

  ☞ take into account correlations between different ZZV couplings

- LHC:

  ➞ the most stringent limits come from $ZZ \to \ell^+\ell^-\not{p}_T$

  ➞ for 10 fb^{-1}, $\Lambda_{FF} = 2$ TeV, form factor power $n = 3$:

$$-6.0 \times 10^{-3} < f_{40}^{Z} < 6.0 \times 10^{-3}$$
$$-7.2 \times 10^{-3} < f_{40}^{\gamma} < 7.2 \times 10^{-3}$$
$$-6.0 \times 10^{-3} < f_{50}^{Z} < 6.2 \times 10^{-3}$$
$$-7.5 \times 10^{-3} < f_{50}^{\gamma} < 7.2 \times 10^{-3}$$

  at 95% CL

  ➞ the limits from $ZZ \to 4$ leptons are a factor 2 weaker

→ the limits from $ZZ \to \ell^+\ell^- jj$ ($ZZ \to \not{p}_T jj$) are a factor 4 (2.5) weaker (Zjj background!)

→ for 100 fb^{-1} the limits improve by about a factor 2

→ increasing Λ_{FF} from 2 TeV to 3 TeV strengthens the bounds by about a factor 2

→ for comparison: present LEP2 limits:

$$|f_4^Z| < 0.49 \qquad |f_4^\gamma| < 0.82$$
$$|f_5^Z| < 1.1 \qquad |f_5^\gamma| < 1.1$$

☞ and the expected limits from Run II
$p\bar{p}$, $\sqrt{s} = 2$ TeV, 2 fb^{-1}, $\Lambda_{FF} = 0.75$ TeV, $n = 3$:

$$-0.17 < f_{40}^Z < 0.17 \qquad -0.18 < f_{40}^\gamma < 0.18$$
$$-0.20 < f_{50}^Z < 0.17 \qquad -0.20 < f_{50}^\gamma < 0.18$$

at 95% CL

→ the most stringent Tevatron limits come from $ZZ \to \ell^+\ell^- \not{p}_T$ and $ZZ \to \not{p}_T jj$

4 – Conclusions

- ZZ production at the LHC will allow for a precise test of the ZZV couplings
- the $ZZ \to \ell^+\ell^-\not{p}_T$ channel is the one most sensitive to ZZV couplings
- backgrounds limit the sensitivity in the $ZZ \to \ell^+\ell^- jj$ and $ZZ \to \not{p}_T jj$ channels
- the SM 1-loop prediction for the ZZV couplings cannot be tested at the LHC (ditto for the Tevatron and a Linear Collider)